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DIRECTIONAL DETECTION OF DARK MATTER

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Abstract. Directional detection is a promising Dark Matter search strategy. Taking advantage on the rotation of the Solar system around the galactic center through the Dark Matter halo, it allows to show a direction dependence of WIMP events. It requires the simultaneous measurement of the energy and the 3D track of low energy recoils, which is a common challenge for all current projects of directional detectors. The third CYGNUS workshop on directional dark matter detection has brought together the scientific community working on both theoretical and experimental aspects of the subject. In this paper, we give an introductory revue of directional detection of Dark Matter, focusing on the main recent progresses.

1 Introduction

Directional detection of Dark Matter has been first proposed as *a powerful tool* to identify genuine WIMP events as such, *even with a low angular resolution detector* (Spergel 1988). More than twenty years later, we give a state of the art revue of directional detection of Dark Matter. Two points will be addressed :

- can directional detection bring something new to the field of Dark Matter search ? This is obviously a major issue, given the timescale to build a large directional TPC.
- what are the main key experimental issues that must be addressed in order to access such promising results ?

2 Directional detection

2.1 Directional detectors

Following early experimental works (Gerbier 1990, Buckland 1994), several Dark Matter directional detectors (Ahlen *et al.* 2010) are being developed and/or oper-

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ated : DM-TPC (Ahlen *et al.* 2011), DRIFT (Daw *et al.* 2010), D^3 (Vahsen *et al.* 2011), Emulsions (Naka *et al.* 2011), MIMAC (Santos *et al.* 2011) and NEWAGE (Miuchi *et al.* 2010). Directional detection requires the simultaneous measurement of the recoil energy (E_R) and the 3D track (Ω_R) of low energy recoils, thus allowing to evaluate the double-differential spectrum $\mathrm{d}^2R/\mathrm{d}E_R\mathrm{d}\Omega_R$ down to the energy threshold. This can be achieved with low pressure gaseous detectors (TPC) and several gases have been suggested : CF_4, ^3He, C_4H_{10} or CS_2.

2.2 *Experimental issues*

There is a worldwide effort toward the development of a large TPC devoted to directional detection (Ahlen *et al.* 2010) and all current projects face common challenges amongst which the reconstruction of low energy tracks seems to be the main one. In the following, we discuss the key experimental issues for directional detection.

2.2.1 Track reconstruction

As far as directional detection is concerned, the estimation of the initial recoil direction is compulsory. This gives an intrinsic limitation of this detection strategy as recoil tracks in low pressure gaseous detectors would encounter a rather large angular dispersion ("straggling" effect). Then, when measuring tracks in a gaseous TPC, the electron drift properties implies a transverse and longitudinal diffusion which contributes to the angular resolution.
Hence, data of upcoming directional detectors should suffer from rather large angular resolution. Dedicated data analysis is needed (Billard *et al.* 2011) and experimental evaluation of the angular resolution should be done through detector commissioning, using e.g. an ion beam or neutron field. A degradation of the angular resolution results in a WIMP-induced distribution getting less anisotropic and hence closer to the expected background one.
The track spatial resolution is also an issue worth being mentionned. It includes resolution in the anode plane as well as along the third dimension (drift space). As shown in (Billard *et al.* 2011), a good spatial resolution, $\mathcal{O}(mm)$, could be obtained in principle, thus opening the way to detector fiducialization to reject surface events.
Other track observables, such as the track length or differential angular deviation, may be used to discriminate electrons from recoils.

2.2.2 Sense recognition

Not only should the track be 3D-reconstructed, but its sense should also be retrieved from the data analysis. Without sense recognition, the expected WIMP-induced distribution becomes less anisotropic and thus gets closer to the expected background event distribution. This induces an obvious loss of discrimination power.

As outlined in (Billard *et al.* 2011), an asymmetry between upgoing and downgoing tracks is expected, due to two different effects. First, the angular dispersion of recoiling tracks should result in a shape asymmetry as the beginning of the track should be more rectilinear than its end. Second, a charge collection asymmetry is expected as dE/dx is decreasing with energy at low recoil energy. Hence, more primary electrons should be generated at the beginning of the track.
Even though several experimental progresses have been done (Dujmic *et al.* 2008, Burgos *et al.* 2010, Majewski *et al.* 2010), sense recognition remains a key and challenging experimental issue for directional detection of Dark Matter. In particular, it should still be demonstrated that sense recognition may be achieved at low recoil energy, where most WIMP events reside, and with which efficiency. For a given directional detector, we argue that the main concern on the head-tail subject is : *how much sense recongnition can be achieved ?* Indeed, directional data should be only partialy sense-recognized, *i.e.* a strong dependence of the sense recognition efficiency is expected on the energy and the drift distance.

2.2.3 Energy threshold

As for direction-insensitive direct detection, the energy threshold plays a key role for directional detection. It is worth emphasizing that it is the lowest energy at which both the initial recoil direction and the energy can be retrieved, what makes it even more challenging for directional detection. In particular, this directional threshold is higher than the threshold for simply detecting recoils. Indeed, a low energy recoil (a few keV) in a low pressure TPC presents a short track length, implying a small number of images, and a large angular dispersion, implying a loss of the direction information. The directional energy threshold is closely related to the gas pressure, the target choice, as well as the read-out and data analysis strategy. There are two main and competing consequences when increasing the energy threshold : a reduction of the number of the expected WIMP events and a sensitivity to the most anisotropic part of the WIMP induced recoil distribution.

2.2.4 Residual background contamination

Zero background is often referred to as the ultimate goal for the next generation of direct detection experiments in deep underground laboratories. However, owing to the large intrinsic difference between the WIMP-induced and background-induced spectra, directional detection could accommodate to a sizeable background contamination (sec. 3.1). It suggests the idea that a light shielding might be sufficient, thus allowing to reduce muon-induced neutron background (Mei & Hime 2006).
Discrimination of background electron recoils from nuclear recoils remains of course a fundamental requirement of experiments aiming to detect WIMP dark matter. For a gaseous directional detector, this could be achieved by means of a selection on the energy/track-length, as for a given energy an electron track is expected to be much longer than a recoil one. However, it should still be demonstrated which rejection power can be obtained with such a selection.

Nevertheless, the background rate estimation remains also as a key point of the directional data analysis strategy, not for the value itself but for the fact that a wrong background estimation may induce bias for Dark Matter parameters.

2.2.5 Energy measurement

The difficulties encountered by the various directional projects in energy measurement are not specific to the directional strategy but to the choice of a low pressure gaseous TPC and the need to measure low energy recoils. First, a precise energy measurement requires a precise calibration and hence low energy references should be used. Second, the detector allows to measure the ionization energy which should then be converted to a recoil energy thanks to the knowledge of the ionization quenching factor. For a given gas mixture, this quantity needs to be precisely measured (Santos *et al.* 2008).

2.3 Directional target

As outlined above, the reconstruction of low energy tracks is the main challenge for the future of directional detection. It follows that the target nucleus must be light to maximize the track length and, in the case of gaseous detectors, the pressure must be as low as possible, leading to rather small detector masses as the volume cannot be arbitrarly large. One may then come to the conclusion that directional detection strategy should focus on spin-dependent interaction to be competitive with planned and existing direct detectors. The detector design should be flexible enough to be able to run with different targets.
Then, the ideal directional target is a light nucleus with non-vanishing spin. Leading candidates include : ^{1}H, ^{3}He and ^{19}F which has been early suggested as a golden target for spin-dependent dark matter searches (Ellis & Flores 1991). Thanks to its good ionization properties (Caldwell *et al.* 2009), CF_4 is planned as a sensitive medium for most upcoming directional detectors (Ahlen *et al.* 2010).
In the following, we present the case for a low exposure (30 kg.year) CF_4 TPC, operated at low pressure and allowing 3D track reconstruction, with sense recognition down to the energy threshold.

3 Directional detection : a powerful tool ?

Directional detection strategy consists in searching for a forward/backward asymmetry in the distribution of WIMP events with respect to the direction of motion of the Solar system, which happens to be roughly in the direction of the Cygnus constellation ($\ell_\odot = 90°, b_\odot = 0°$ in galactic coordinates). As the background distribution is expected to be isotropic in the galactic restframe, one expects a clear and unambiguous difference between the WIMP signal and the background one.

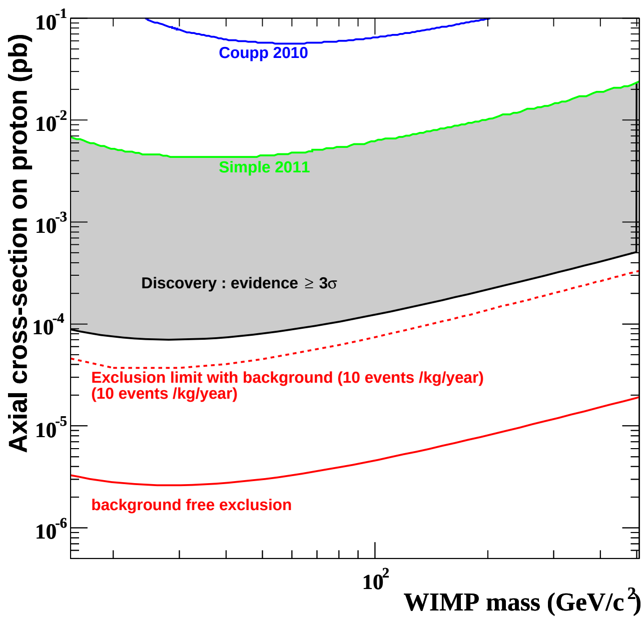

Fig. 1. *Spin dependent cross section on proton (pb) as a function of the WIMP mass* (GeV/c^2)*, in the pure-proton approximation. Exclusion limits from (Behnke et al. 2011) (dark blue) and (Felizardo et al. 2011) (dark green) are shown. The projected exclusion limit of a forthcoming directional detector (30 kg.year) is presented in two cases : background-free (light blue solid line) and with a background rate of 10 events/kg/year with sense recognition (dot-dashed line). For the same exposure, the shaded area presents the* 3σ *discovery region.*

3.1 Dark Matter exclusion with Directional detection

At first, one may think of using directional detection to set exclusion limits. Several methods have been proposed (Henderson 2008, Billard *et al.* 2010b), amongst which the *Directional Likelihood exclusion method* (Billard *et al.* 2010b) is the most conservative one as it uses only the angular part of the event distribution, to avoid assumptions on the unknown energy spectrum of the background. It considers the theoretical angular distributions of both WIMP and background events in order to set the most restrictive limits.
In the case of a low exposure (30 kg.year) CF_4 directional detector, it has been shown that exclusion limits down to $\sim 10^{-5}$ pb for highly background-contaminated data or down to $\sim 10^{-6}$ pb for background-free data (sensitivity) may be reached, see fig. 1. As expected, increasing the number of background events induces an upward shift of the cross section limit. However, taking full advantage on the

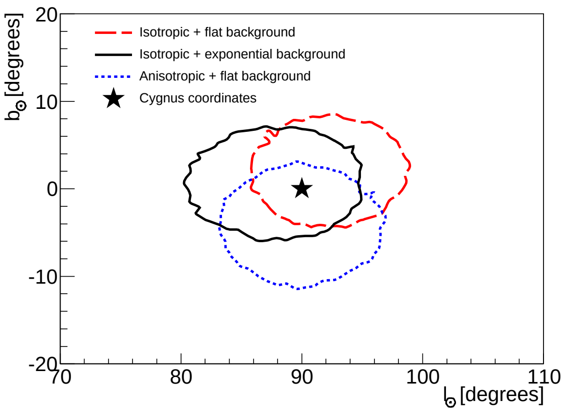

Fig. 2. 95% contour level in the (ℓ, b) plan for various input models : Isotropic/anisotropic halo model, flat/exponential background. In all cases, the signal is proved to be in the direction of the Cygnus constellation. Figure from (Billard *et al.* 2011).

knowledge of the expected WIMP and background angular distributions in the data analysis allows to be less sensitive to background contamination. This is definitely a major advantage of directional detection.

3.2 Rejecting the isotropy with directional detection

Using the clear and unambiguous difference between WIMP signal and background, directional detection may also be used to prove that the directional data are not compatible with background. With the help of unbinned likelihood method (Copi & Krauss 1999) or non-parametric statistical tests on unbinned data (Green & Morgan 2007), it has been shown that a few number of events $\mathcal{O}(10)$ is required to reject the isotropy, and hence prove the data are not compatible with the expected background. This may give a decisive contribution of directional detection to the field of Dark Matter, especially at the present stage when non-directional experiments start to observe candidate events whose origin is difficult to assess (Ahmed *et al.* 2011, Aprile *et al.* 2011, Aalseth *et al.* 2011, 1).

3.3 Dark Matter discovery with directional detection

Directional detection may also be used to discover Dark Matter (Billard 2010a, Green & Morgan 2010). In particular, the method proposed in (Billard 2010a) is a blind likelihood analysis, the proof of discovery being the fact that the signal points to the direction of the Cygnus constellation (to which the solar system's velocity vector is pointing). As shown on fig. 2, the main direction of the incoming events matches the expected direction within 10° to 20°, thus providing a unique

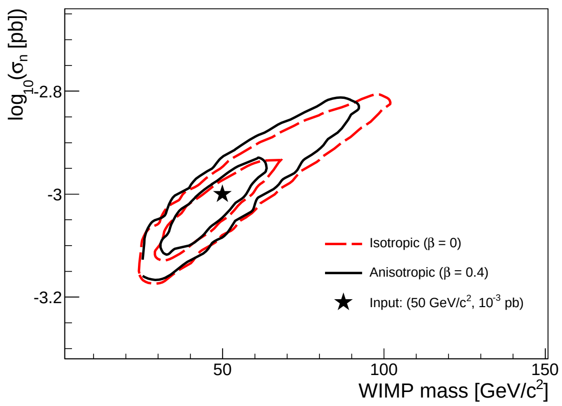

Fig. 3. 68% and 95% contour level in the (m_χ, σ_n) plane, for a 50 GeV/c^2 WIMP and two input halo models : isotropic and triaxial. Figure from (Billard *et al.* 2011).

signature of their origin. Hence, the goal of this new approach is not to reject the background hypothesis, but rather to identify a genuine WIMP signal as such.
Even at low exposure, a high significance discovery is achievable, even in the presence of a sizeable background contamination and for various detector configurations (Billard *et al.* 2011b). Figure 1 presents the region in the (m_χ, σ_p^{SD}) plane for which a discovery with a significance greater than 3σ may be reached with a 30 kg.year CF_4 directional detector. It corresponds to a rather large region in the SUSY parameter space (Albornoz-Vasquez 2011), well below current limits from both proton and neutron-based detectors. This highlights the fact that directional detection is of major interest to clearly identify a positive Dark Matter detection.

3.4 Dark Matter identification with directional detection

For high WIMP-nucleon cross section, it is also possible to go further (Billard *et al.* 2011). With the help of a high dimensional mutivariate analysis, it is possible to identify WIMP Dark Matter with directional detection. It has been shown that dedicated analysis of simulated data of a 30 kg.year CF_4 directional detector would allow us to constrain the WIMP properties, both from particle physics (m_χ, σ_p^{SD}) and galactic halo (velocity dispersions).
As an example, fig. 3 presents the 68% and 95% contour level in the (m_χ, σ_n) plane. This is indeed a measurement of the WIMP properties, consistent with the input values, with a rather small dispersion and model-independent as the velocity dispersions are set as free parameters within the framework of a multivariate Gaussian velocity distribution.

4 Conclusion

A 30 kg.year CF_4 directional detector would offer a unique opportunity in Dark Matter search, by leading, depending on the value of the unknown WIMP-nucleon cross section, either to a conclusive exclusion, a high significance discovery of galactic Dark Matter or even an estimation of the WIMP properties. However, several key experimental issues need to be addressed to achieve these physical goals, both on the detector side and on the data analysis one.

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